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OPERATION JANGLE PROJECT 4.5 EVALUATION OF MISSILE HAZARD, UNDERGROUND SHOT

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Stanford Research Institute
Stanford, California

May 1952

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OPERATION JANGLE

PROJECT 4.5

EVALUATION OF MISSILE HAZARD, UNDERGROUND SHOT

By

R. B. Vaile Jr. and V. Salmon

May 1952

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Acknowledgement is made for assistance received from the Naval Radiological Defense Laboratory. The Laboratory made available facilities for weighing samples and transported them from Nevada to the laboratory.

CONTENTS

ILLUSTRATIONS

CHAPTER 3 DESCRIPTION OF THE EXPERIMENT

CHAPTER 4 RESULTS

CHAPTER 5 DISCUSSION

TABLES

CHAPTER 4 RESULTS

PROJECT 4.5

ABSTRACT

The missile experiment performed as a part of the JANGLE underground explosion test demonstrated that reinforced concrete walls and highways located 40 feet to 140 feet from ground zero were broken and thrown out as missiles. Material nearer than 40 feet (or perhaps 50 feet) was vaporized or pulverized to the extent that it was largely windborne.

Missiles of military significance were found 400 feet to 3300 feet from ground zero. Those of major significance were in the range 400 feet to 1500 feet.

Analysis has permitted estimates of the missile hazard from an underground explosion of roughly 25 times the energy release of the JANGLE underground explosion (and at the same scaled depth, $\lambda_c = 0.15$) fired under a continuous reinforced concrete runway 18 inches thick. It is predicted that missiles would produce serious damage to buildings out to a radius of 1100 feet and to airplanes out to 3000 feet. These figures should be compared to estimates that the air blast from such an explosion would damage buildings to 2200 feet and airplanes to 6000 feet.

It is concluded that on large shallow underground explosions damage by the mechanism of air blast will extend farther than damage by the mechanism of missiles. This conclusion is sufficiently firm that no further missile experiments appear necessary.

CHAPTER 1

INTRODUCTION

1.1 HISTORICAL

The hazards of missiles from underground explosions became of interest in 1950 during a time when an underground nuclear test was proposed for Amchitka Island where the soil contains rocks and boulders. Because of this interest an experimental study of missiles was added to the underground (HE) explosion tests at Dugway in 1951.

The Dugway tests revealed such large ranges for missiles that a further experimental study of missiles was added to the program of the JANGLE underground explosion at the Nevada Test Site in December 1951 as Project 4.5.

1.2 OBJECTIVE

The over-all purpose of Project 4.5 was to obtain data leading toward the determination of the damage produced by missiles as a result of underground nuclear explosions. Evaluation of the damage to be expected from missiles is important to the extent that it affects the choice of an underground weapon rather than an air-burst weapon against any class of target.

The specific objective of Project 4.5 was to obtain data on the underground shot of Operation JANGLE in regard to the range, size, and source location of potentially damaging missiles produced from a typical concrete highway or landing strip, and a typical concrete wall of a type that might be used in a small factory building of several stories.

CHAPTER 2

BACKGROUND DISCUSSION

2.1 INTERIOR BALLISTICS

The design of the JANGLE missile experiment was particularly difficult because of the extremely meager quantitative information available regarding missiles from underground explosions. It was desired to obtain, both before the experiment and as a result of the test, information on (1) the formation and ejection of missiles from target sources (interior ballistics) and (2) the ballistic behavior of whatever missiles are formed (exterior ballistics).

The formation of missiles is primarily a matter of the breakup of materials under shock conditions and, in the case of nuclear explosions, of their response to temperature shock as well.

While quarrying operations using high explosives have been carried on for many years, the intent in such explosions is to minimize the production of missiles, and no quantitative information on the size and ballistic characteristics of missiles incidentally produced has been found. A considerable amount of work on the fracture of solids has been carried out for use in problems of coal handling and ore crushing, and the possible application of this work to missile formation is of interest. However, the shock intensity produced by nuclear explosions is of a different order of magnitude than that produced by any of the methods considered in the literature and hence there was no reason to expect previous experience to be particularly useful in planning this experiment. As a result, an important component objective of this test was the determination of the extent of breakup of ordinary concrete construction when subjected to a nearby underground nuclear explosion.

2.2 EXTERIOR BALLISTICS

In regard to the ballistic behavior of whatever missiles are produced, some information was available prior to the design of this test. That information consisted of the results of an experiment with artificial missiles salted in the backfill of the underground HE explosions in dry clay at Dugway during May of 1951. At Dugway, one of the most difficult elements of the experiment was the detection

of missiles for recovery after the explosion,* and this experience influenced the design of the JANGLE missile experiment.

The Dugway tests confirmed the expectation that missiles would follow trajectories lying approximately in vertical radial planes passing through the charge center and the missile in the backfill; this finding is also reflected in the design of the collection strips at JANGLE.

It had been estimated that missiles would be thrown out with initial velocities approximately the same as those of the surface particles in their path and that their external ballistic behavior would be adequately predictable if their size, shape, and density were known. The results of the Dugway experiments were consistent with this estimate.

The analysis procedure developed in the cited Dugway report was used for prediction of missile behavior in the JANGLE underground shot. This analysis is given on pages 23 to 26 of that report. In it the expected ranges are computed for possible missiles composed of Portland cement concrete of sizes from 2 inches to 8 inches and with initial zenith velocities between 5,000 and 20,000 feet per second. Detailed analysis based on photographic evidence has indicated that the drag coefficient assumed for the Dugway analysis was too high; downward revision of it has yielded a changed formula (with smaller values) for the initial velocities of missiles at Dugway:

$v = 750 \sin^2\theta$, where v is the initial velocity of a missile in feet per second and θ is the elevation angle of the slant radius from the charge to the initial position of the missile in the backfill. Similar correction of drag coefficients and initial velocities assumed for JANGLE might affect the range and density predictions, but certainly to a far smaller extent than the other uncertainties involved, particularly those concerning the nature of the breakup.

Discussion with personnel of the Armed Forces Special Weapons Project and the Technical Operations Squadron before the test led to agreement that the source of missiles of greatest interest was concrete highways (or landing strips) of typical modern reinforced concrete construction. It was also agreed that a missile source of secondary interest was a reinforced concrete wall such as might be used in a low, multi-storied, reinforced concrete building.

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*These experiments are reported in Technical Report No. 5, dated November 15, 1951, "Behavior of Missiles in Underground Explosions at Dugway", by Stanford Research Institute, under Contract N7onr32104 (Project 317, Rabbit) for the Office of Naval Research; classification, SECRET.

2.3 EXTRAPOLATION

Extrapolation of the results of one experiment to what may be expected from a larger scale experiment requires consideration of both exterior and interior ballistics.

In general, the scaling laws for interior and exterior ballistics will be different. Breaking of missile source material presents a problem for which very little direct information exists. Newmark has shown* that the failure of reinforced concrete beams, when subjected to the blow of a falling hammer, depends on the energy absorbed from the hammer and utilized in cracking the concrete and rupturing the reinforcing material. While this method of loading the concrete is much slower than the process by which an explosion breaks up missile source material, it furnishes a criterion of breakup which has some experimentally demonstrated validity. Thus on this basis the extent of breakup is proportional to the energy absorbed during the breakup process which, in turn, may be considered proportional to the energy-density in the shock wave in the earth. Since the unit of energy-density has the same dimensions as pressure it scales in the same manner. Hence on a series of ideal scaled experiments, the same energy-density in the shock wave will exist at the same scaled distances from the charge. Thus,

$$S = \left[\frac{W_2^{1/3}}{W_1^{1/3}}\right] = \frac{E_2^{1/3}}{E_1^{1/3}}$$

$$(ED)_1 = \beta \frac{E_1}{r_1^3}$$

$$(ED)_2 = \beta \frac{E_2}{r_2^3} = \beta \frac{S^3 E_1}{r_2^3}$$

If $(ED)_1 = (ED)_2$, then

$$\beta \frac{E_1}{r_1^3} = \beta \frac{S^3 E_1}{r_2^3}$$

*"Methods of Analysis for Structures Subjected to Dynamic Loading", N. M. Newmark, prepared for Physical Vulnerability Branch, Air Targets Division, Directorate of Intelligence, USAF, March 1951.

or $\quad r_2^3 = S^3 r_1^3$

therefore $r_2 = Sr_1$

where
- S = the scale factor
- W = weight of charge in equivalent pounds of TNT
- E = energy
- ED = energy-density
- β = a factor of proportionality
- r = distance in feet from ground zero.

It can be postulated that the breaking up of a solid body depends on the stresses which accelerate the internal parts of it when the whole body is subjected to unbalanced external forces. On this basis peak acceleration is a criterion of breakup. If scaling laws are combined with experimental evidence regarding the variation of peak acceleration with distance on any one explosion it can be shown that as the charge size is increased, the scaled radius for a given value of acceleration decreases. Further analysis of this point is presented in Chapter 5 and a complete discussion of scaling laws may be found in an early report by C. W. Lampson.*

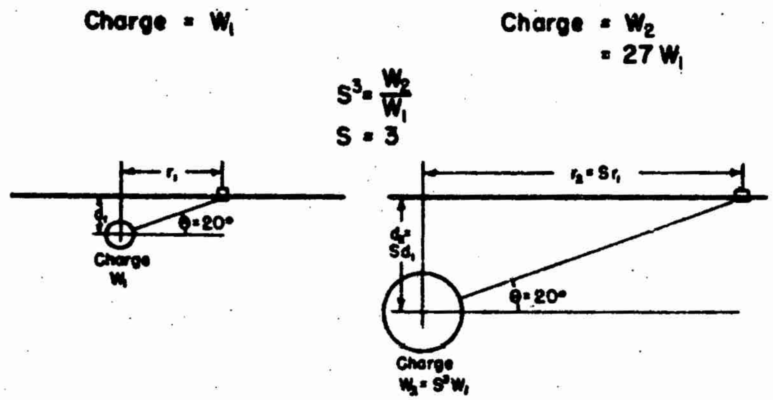
Accompanying breakup is the ejection of the missiles. For the calculation of the exterior ballistics portion of the problem it is necessary to know the velocity and the angle at which missiles are initially ejected. Experience with missiles at Dugway indicates that the velocity-angle relation is of the form

$$v = \frac{V_{oo}}{\lambda_c^n} (\sin \theta)^n.$$

*"Final Report on Effects of Underground Explosions", C. W. Lampson, Division 2, National Defense Research Committee of the Office of Scientific Research and Development, NDRC Report No. A-479, OSRD Report No. 6645, March 1946.

In this, λ_c is the scaled depth of charge;
θ is the elevation angle of the radius vector from charge to missile;
n is an exponent of the order of 1 or 2;
V_{oo} is a constant, presumably dependent largely on some characteristics of the soil. Implicit in this relation is the assumption that missiles are ejected radially from the charge.

From the velocity and elevation angle of ejection, together with the drag coefficient of the missile, it is possible to calculate by the standard methods of external ballistics the horizontal range, the maximum altitude, the time of flight, and the angle of striking of the missile. In a series of scaled experiments, missiles originating at the same angle will originate at constant scaled distance from ground zero.



Since λ_c would be held constant in a series of scaled experiments, the ejection velocity, v, is independent of the scale of the experiment. Thus the horizontal ballistic range is independent of the scale of the experiment. The total range, as measured from ground zero, will consist, however, of the sum of this ballistic range and the distance from ground zero of the point of origin of the particular missile considered. This may be expressed by $R = ar_c + r_b(\theta)$, where R is the total range; ar_c is the distance from ground zero to point of origin of the missile, expressed as a fraction, a, of the crater radius, r_c; and $r_b(\theta)$ is the ballistic range which depends only on θ, the elevation angle of the slant radius from charge to missile source.

In a series of scaled experiments a is held constant and r_c is believed to be proportional to the scale factor. When the scale of an

experiment is increased, this relation indicates that the total range, R, will increase, but not as rapidly as the scale factor, because r_b is constant. The point at which the two components of the range are equal must be determined by experimental evidence.

2.4 CALCULATION OF POTENTIAL DAMAGE

After conclusions are reached about missile behavior, and extrapolations are made to other situations, a criterion of damage must be established for assessing the importance of missiles. It is considered important and valuable to know under what circumstances missiles might be sufficiently concentrated and possess sufficient velocity to cause actual demolition of buildings. For this purpose data obtained at Dugway on the amount of throwout which actually caused collapse of test structures was used to develop such a damage criterion.

In regard to airplanes, it is ultimately necessary to know both the concentration and size of missiles which will damage airplanes, as well as the concentration and sizes of missiles which will arrive at any specified radius from ground zero. During the analysis reported here, no quantitative information regarding the effectiveness of missiles in damaging airplanes has been available, and commonsense estimates have therefore been used in determining the limiting size and concentration of missiles considered.

Final conclusions regarding missile hazard must be based on comparison with the hazard produced by other mechanisms, such as air blast and ground motion.* In estimating the hazards of air blast and ground motion, extrapolation to larger charges requires careful consideration of the effect of soil characteristics. Information from Dugway and from the HE-1, HE-2, and HE-3 shots at JANGLE as to levels of peak air-blast pressure and impulse have been used as a basis for comparison with missile damage.

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*Data for these comparisons has come primarily from two preliminary reports of phases of Operation JANGLE. The two reports, both by E. B. Doll and V. Salmon of SRI in April, 1952, are: "Ground Acceleration, Ground and Air Pressures for Underground Test, Project 1(9)a", Contract N7onr32104, for the Office of Naval Research; "Scaled HE Tests, Project 1(9)1", Contract DA 49-129-eng-119, for the Office of the Chief of Engineers.

CHAPTER 3

DESCRIPTION OF THE EXPERIMENT

3.1 GENERAL

As a result of the considerations just enumerated, a group of concrete highway strips was laid out together with a collection area along the central radius, in accordance with the plans shown in Figures 3.1 and 3.2. These are the A targets and collection area. A similar array of walls and collection area was laid out as shown in Figures 3.1 to 3.5, under the designation of B targets and collection area. As a result of the Dugway experiments, it was estimated that the missiles having the greatest range would come initially from locations where they would have elevation angles of 45 to 60 degrees (assuming that their initial velocity was along the slant radius from the charge to the target).

3.2 CONSTRUCTION

To permit determination of the source location of missiles that were recovered after the explosion, the highway slabs were poured in small sections, each containing a different combination of pigment and aggregate. Similarly, each of the walls contained a different pigment. Since the greatest interest was thought to lie in the highway slab nearest ground zero, designated A1, That slab was divided up into five subsections, as indicated in Figures 3.1 and 3.3. While each of these subsections had a different pigment, the reinforcing steel was continuous across the section boundaries and the concrete was placed in rapid sequence (this whole target was poured in one day) so that a good mechanical bond was obtained even though there was color separation. In order to make certain of the identification of missiles stemming from the A1 targets, all of these were poured with special aggregate. The aggregate used consisted of crushed red brick plus 50 pounds of 3d aluminum nails per cubic yard of concrete. In addition, specific pigments were used to designate the separate sections of this target. The remaining A targets (A2 to A5) were poured with the ordinary gravel aggregate, used in all the construction at the site, and this aggregate was also used on all the walls which comprised the B targets, as shown in Figure 3.6.

Test samples were poured at the same time all these targets were placed and additional test samples were obtained by coring after the targets had been in place for at least 28 days. All these test samples were given compression tests by the Pittsburgh Testing Laboratory and all were found to have strengths in the range 3,000 psi to 4,000 psi (California State Highway Specifications require 3,000 psi in primary

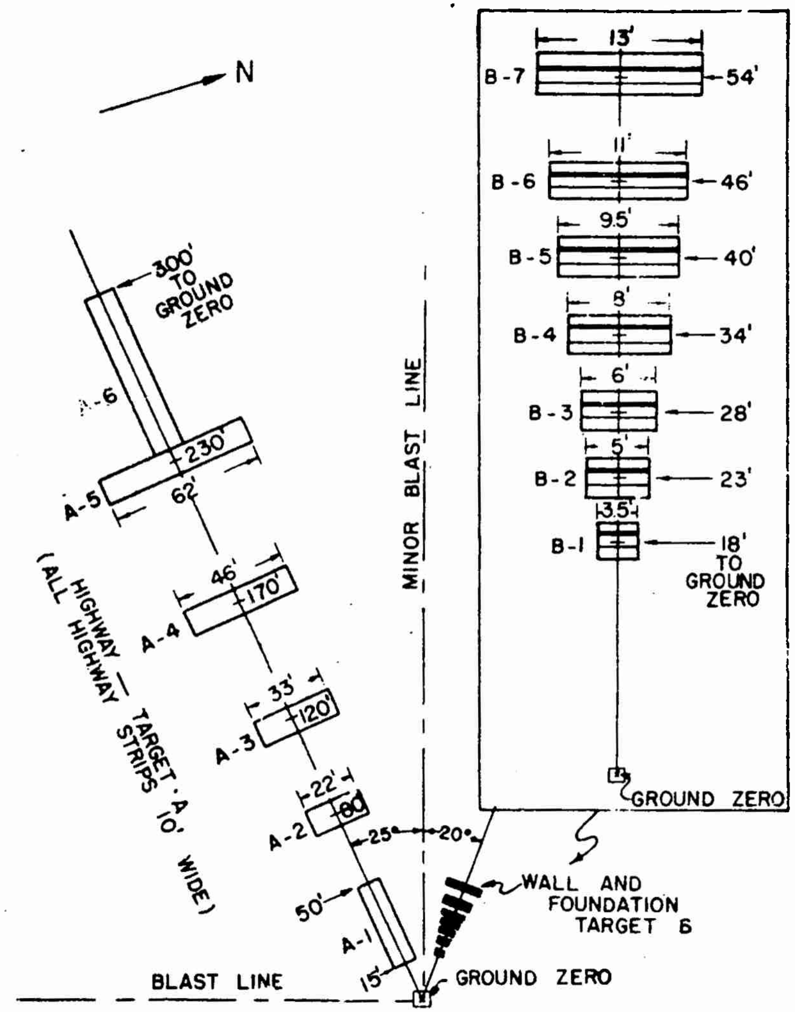


Figure 3.1 Target (Missile Source) Layout

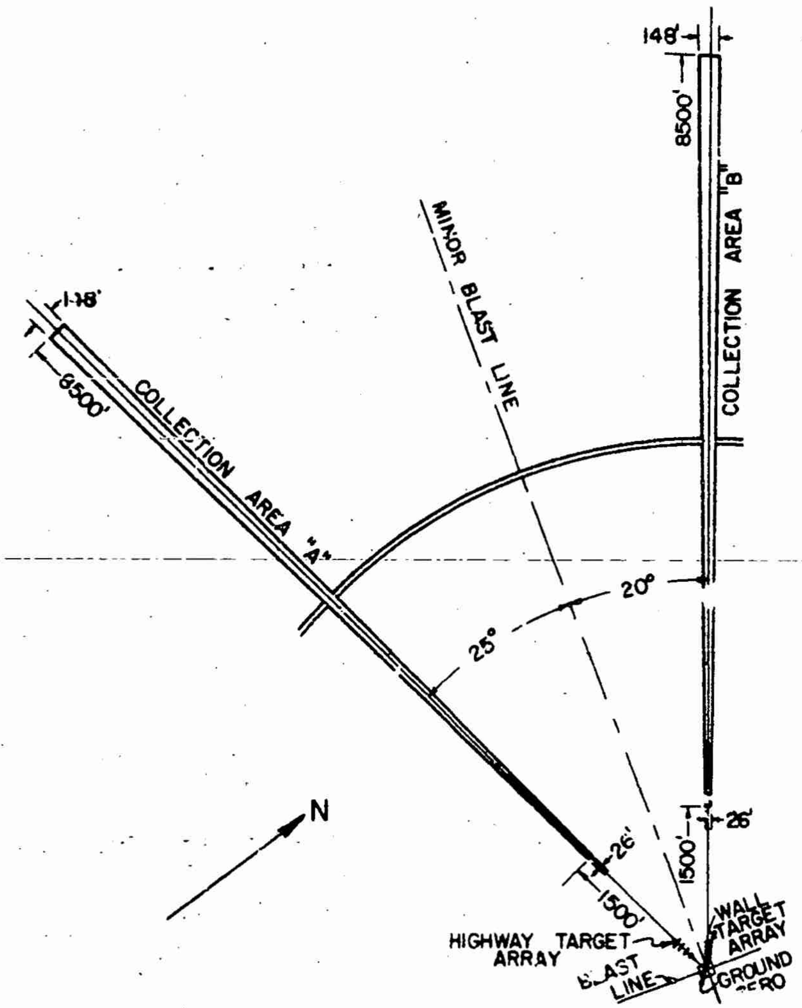


Figure 3.2 Collection Strip Layout

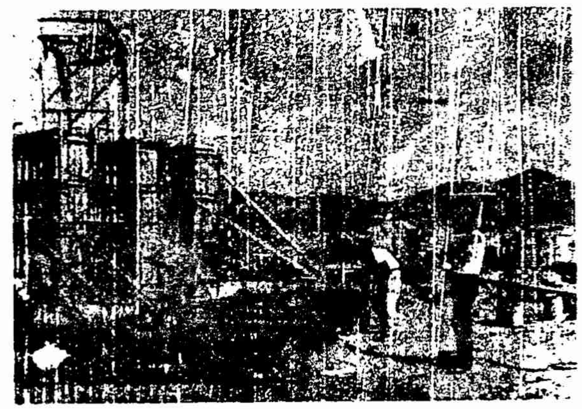


Figure 3.3 Target A-1 in Preparation

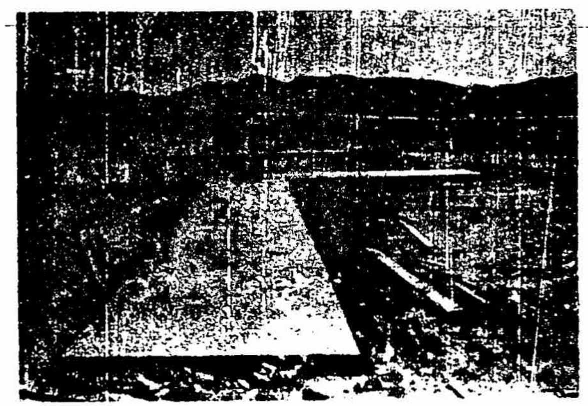
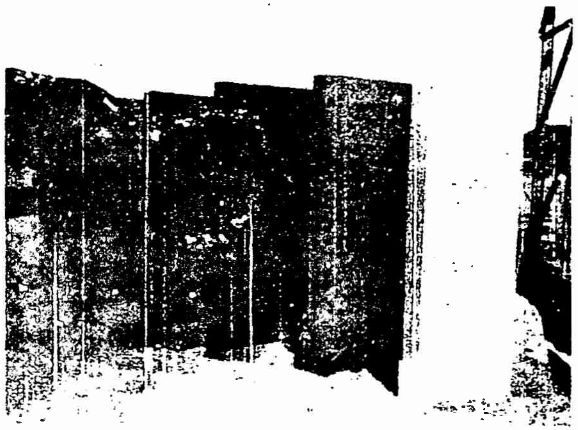


Figure 3.4 View of Highway and Wall Targets



(a)

(b)

Figure 3.5 Pigmented Wall Targets

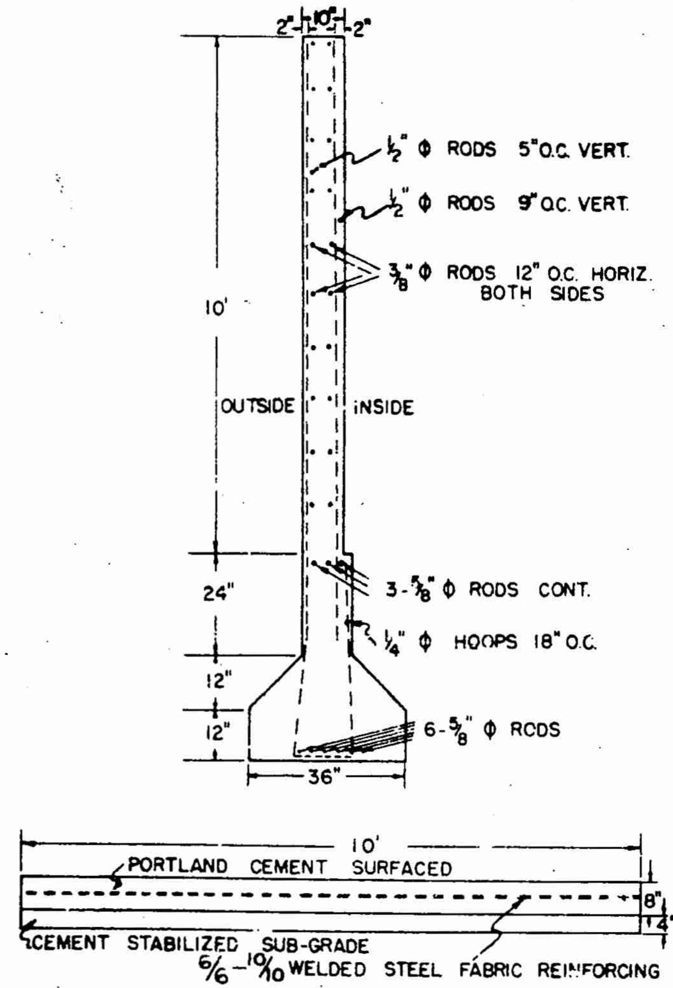


Figure 3.6 Specifications for Wall and Highway Target Construction

highways). These tests demonstrated that the special aggregate (brick and aluminum nails) used in the A1 targets had no effect on the compressive strength under slowly applied load. However, the possibility that they may have affected adversely the strength when subjected to shock loads cannot be neglected.

The collection areas were laid out as specified in Figure 3.2 and then cleared, leveled, and oiled. Both collection areas extended from 1500 feet to 8500 feet in radius. They were surveyed with marked stakes on each side of each collection area at 100-foot intervals in radius.

The construction of the targets and the collection areas was accomplished precisely as specified, and the fact that after the test it became apparent that a somewhat different design of experiment would have given more information implies no criticism of the AEC Field Office or the contractor.

3.3 POST-SHOT OPERATIONS

After the shot, missiles of diameter larger than 2 inches and less than 12 inches were collected. Visual observation made it apparent that the total number which actually landed on the collection strips was much smaller than had been expected and so missiles as far as 50 feet to the sides of collection strip B were also noted and, in many cases, collected, in order to increase the total number available for analysis.

Collected missiles were placed in labeled containers and shipped to NRDL, Hunter's Point, for later weighing on December 20, 19.1

Later analysis disclosed that the large missiles from the white slab at r_o = 80 feet which fell closer to ground zero than the beginning of the collection strip were of special interest, and so an actual survey of these was made on April 1., 1952.

CHAPTER 4

RESULTS

4.1 GENERAL

An over-all survey after the shot revealed a very low density of missiles on the collection strips with almost none beyond a range of 3300 feet.* By and large, the missiles found between 1500 feet and 3300 feet were originally between 30 feet and 50 feet from ground zero.

On the A strip about 20 missiles were collected at ranges between 1500 and 3000 feet. These are shown in Table 4.1. As indicated, most of these were yellow, with the brick aggregate and aluminum nail content identifying them as from source A-1-e. All these missiles were badly fractured and crumbly. It is presumed that the shock actually produced failure in many fracture planes but the missiles hung together during their ballistic flight because of slight geometrical interlocking of the fracture surfaces. Examples are shown in Figures 4.1, 4.2, and 4.3.

Only about 15 missiles were found actually on the B collection strip. It was therefore decided to collect missiles some 50 - 60 feet to the left and right of the strip as well.** This yielded a total of about 130 and permitted some more detailed analysis. Table 4.2 is a description of the collected missiles from wall sources and Table 4.3 shows their range distribution. Examples appear in Figures 4.4, 4.5, 4.6, and 4.7.

A sketch showing the location (as determined by stadia survey) of large missiles from white slab A-2 is shown in Figure 4.9. Photographs of several of these large pieces of slab appear in Figures 4.8, 4.10, 4.11 and 4.12. The three corners which were identified are of special interest because they are the only missiles whose origins can be precisely located within a target. These provide a means of checking the variability both in lateral location and range. If a terminal location of each corner is predicted on the assumption that

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*The exceptions were a 792 gram yellow missile at 3350 feet; a 1500 gram black missile at 3500 feet; a 578 gram yellow missile at 4150 feet; a 5000 gram yellow missile at 5380 feet; and a 10,000 gram red missile at 5500 feet.

**Throughout this report, left and right are specified as the directions when viewed from the charge.

its flight was in a radial plane in accordance with the ballistic behavior of such missiles as predicted by E. W. Paxson,* then the deviations from their predicted locations are as follows (refer to Figure 4.9):

Corner a, 250 feet long, 0.5 degrees left
Corner b, 175 feet short, 4.5 degrees left
Corner c, 125 feet short, 4.9 degrees right
Corner d, not found.

These deviations are believed to represent the uncertainties to be expected of missiles from underground explosions. Deviations of the same order were observed at Dugway.

4.2 SUMMARY

a. Almost all the missiles recovered originated in the three targets having initial locations between 40 feet and 85 feet of ground zero. Less than 5 percent of the nearer targets (40 to 50 feet) is accounted for in the missiles recovered while more than 70 percent of the farther target (75 to 85 feet) is accounted for. Apparently most of the source material within a radius of about 50 feet of ground zero was either vaporized or pulverized to such fine sizes that it was carried by winds, whereas material beyond 85 feet had such short flight that it was covered by the throwout material around the crater rim.

b. The resulting missiles were thrown to distances between 400 feet and 3300 feet of ground zero. The nearer targets were thrown to the greater ranges; missiles from these sources were all smaller than about 6 inches. The farther target produced very large missiles (up to 5 feet) which were thrown to locations between 400 feet and 1500 feet.**

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*"The Trajectories of Surface Fragments Subsequent to an Underground Explosion", E. W. Paxson, Report RM-743, The Rand Corporation, Santa Monica, California, December 1951. Classification SECRET RESTRICTED DATA.

**It should be remembered that the missile sources at JANGLE were not continuous. It is believed that if the intervening spaces (50 to 75 feet and 85 to 115 feet) had contained missile source material, the behavior of the resulting missiles would have been intermediate to that described above and that the concentration of falling missiles would have been considerably greater, particularly at the shorter ranges.

TABLE 4.1

Number of Missiles Recovered on Collection Strip A

Size Categories*: a: 100-400 g b: 400-700 g c: 700-1400 g d: 1400 g up

Range (100's of feet)	Missile Color r_o: Green (23 feet) a	b	c	d	Black (34 feet) a	b	c	d	Red (41 feet) a	b	c	d	Yellow (47 feet) a	b	c	d	White (80 feet) a	b	c	d
15-16	1								4				3		1					
16-17									8				3							
17-18													3		1					
18-19															1					
19-20														1						
20-21																				
21-22															1	1				
28-29																1				

*Corresponding sizes are: 100-400 g, 400-700 g, 700-1400 g, 1400 g up.
Diameter (inches): 1.7 - 2.8, 2.8 - 3.3, 3.3 - 4.2, 4.2 up.

TABLE 4.2

Size and Number of Missiles Recovered from Wall Target Sources

Color of Wall	White	Green	Black	Red	Yellow	Blue
Average Original Distance from Ground Zero	19 feet	24 feet	30 feet	36 feet	42 feet	50 feet
No. missiles collected	0	4	7	15	5	102
Av.wt.of " "(grams)	0	266	227	252	1275	1175
Total wt." " "	0	1065	1589	3782	6374	119,828
Smallest wts. picked up (grams)	0	77	30	26	29	85
Largest wt. found (grams)	0	436	806	677	5000	11,800

TABLE 4.3

Number of Missiles Recovered from Wall Target Sources*

Size Categories: a: 100-400 g, b: 400-700 g, c: 700-1400 g, d: 1400 g up																												
Wall Color (r_o)	White (19 feet)				Green (24 feet)				Black (30 feet)				Red (36 feet)				Yellow (42 feet)				Blue (50 feet)							
Size	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d				
Range in 100's of feet																												
15 - 16	2				1								2								3	3	3					
16 - 17	1												1								5	3	1					
17 - 18	1								3				3								3	5	2	3				
18 - 19													1								7	5	3	2				
19 - 20																					2	3	7	2				
20 - 21													1								5	3	1	2				
21 - 22									1				2								3	1	1	1				
22 - 23																	1				2		2	7				
23 - 24													2				1				2	4	1	1				
24 - 25					3	1							1				1						1	2				
25 - 26									1					1							1		1	1				
26 - 27																							2	1				
27 - 28									1				1	1			2	1					1	3				
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*Collection area = approximately a 5 degree sector, including Collection Strip B (= 1 degree).

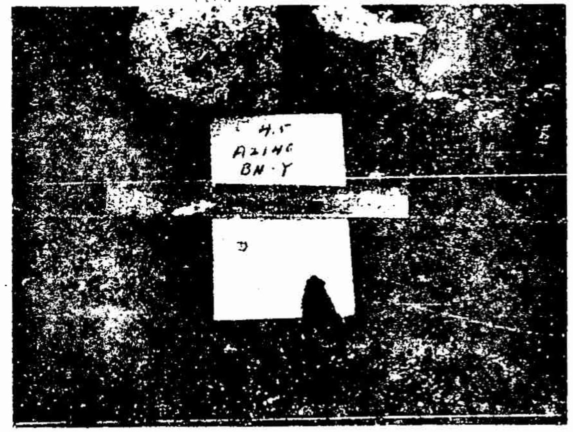

Figure 4.1 Highway Missile, Recovered at 2140 Feet; Originally at 45 Feet

Figure 4.2 Highway Missile, Recovered at 1750 Feet; Originally at 45 Feet

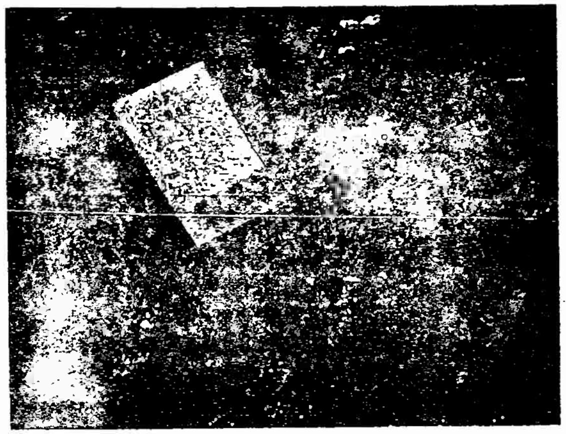

Figure 4.3 Highway Missile, Recovered at 2830 Feet; Originally at 45 Feet

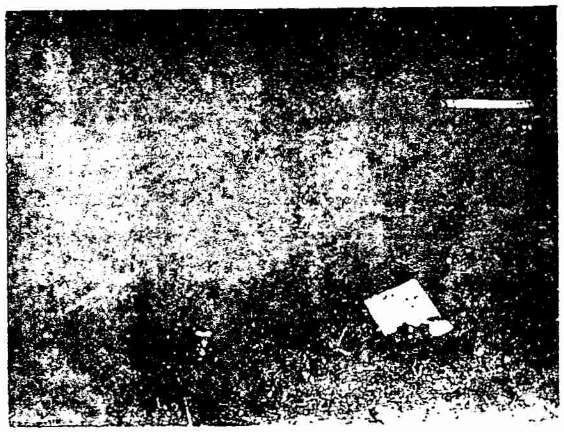

Figure 4.4 Wall Missile, Recovered at 4001 Feet, About 50 Feet to Right of Collection Strip; Originally at 50 Feet. Note Twisted but Unbroken Reinforcing.

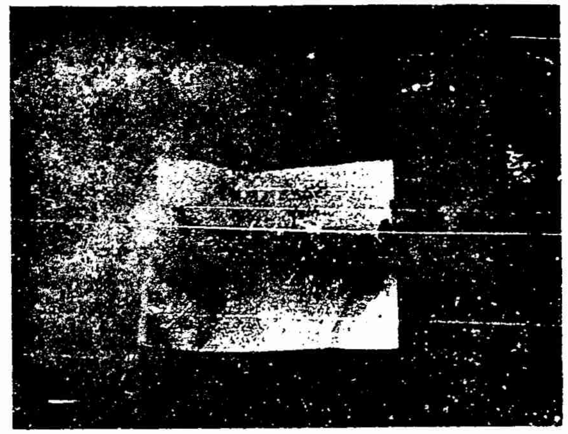

Figure 4.5 Wall Missile, Recovered at 3350 Feet, to Left of Collection Strip; Originally at 42 Feet

Figure 4.6 Wall Missile, Recovered at 2720 Feet, 200 Feet to Right of Collection Strip; Originally at 50 Feet. Note Friability.

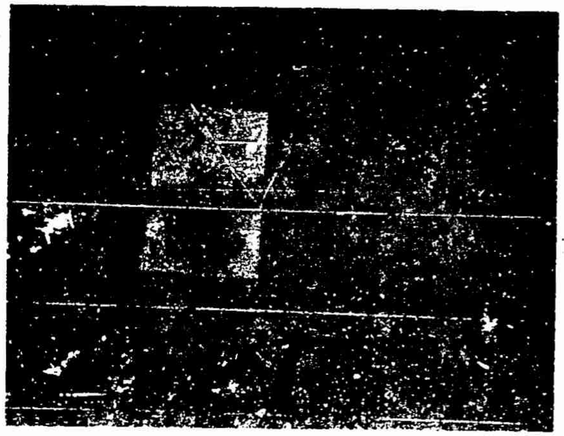

Figure 4.7 Wall Missile, Recovered on Collection Strip at 2250 Feet; Originally at 50 Feet. Note Extensive Fracture.

Figure 4.8 Highway Missile, Found at 1400 Feet; Originally at 80 Feet

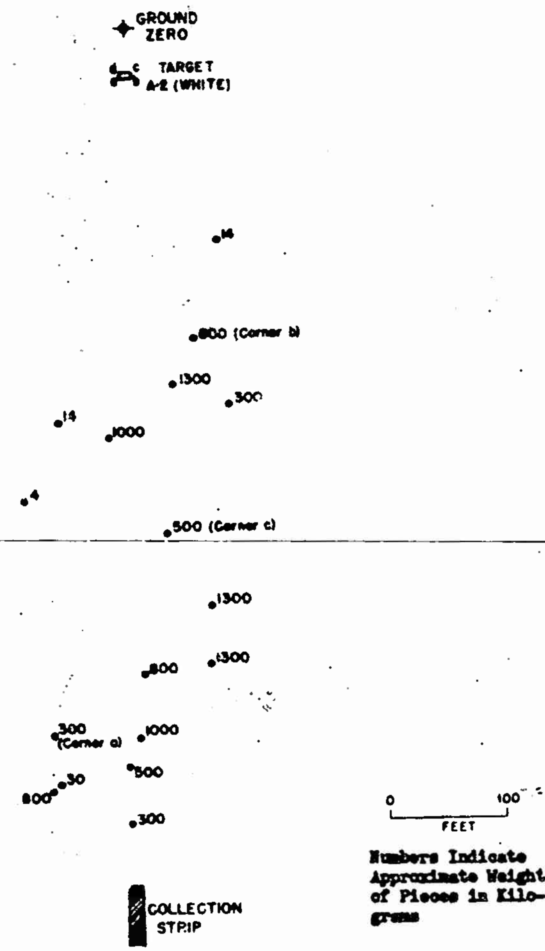

Figure 4.9 Sketch of Location of Missiles from White Highway Slab, Target A-2; Originally at 75 to 85 Feet

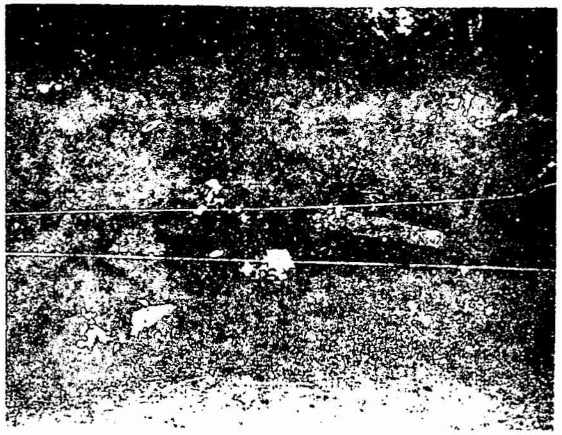

Figure 4.10 Highway Missile, Found at 800 Feet; Originally at 80 Feet

Figure 4.11 Highway Missile, Found at 1000 Feet, About 100 Feet to Left of Center Line; Originally at 80 Feet

Figure 4.12 Highway Missile, Found at 1200 Feet; Originally at 80 Feet

CHAPTER 5

DISCUSSION

5.1 INTERIOR BALLISTICS

The formation of missiles is the most important element in interior ballistics. The breakup of materials such as is produced in rock crushers has occasioned a great deal of study. It seems clear that a single blow should be expected, in a statistical sense at least, to produce a whole range of sizes and most of the published work is aimed toward the analysis or prediction of the distribution of sizes so produced. Enough contradictory publications have been found so that the technical situation for present purposes is definitely not clear. However, both experimentally and from the literature it is plain that missile source material very close to an explosion will be broken into small pieces, while missile source material at great distances will be broken into large pieces or not at all. Superimposed on this over-all picture, however, is the expectation that at any one radius a wide range of sizes will be produced.

Some impression of the way these sizes are thought to be distributed can be obtained from Figure 5.1, in which the log-log of the reciprocal of the percent of total weight of missiles (from a given source) larger than a specific size is plotted against the log of the created surface area for that size. Theoretically, a slope of 0.5 is predicted for such data on the basis of the "Ideal Breakage Law"* and, in experimental situations where the original material is completely collected and accurately measured, excellent fit is usually obtained. At JANGLE, small sizes were not collected at all, and large sizes are always expected to deviate because there is not an infinitely large amount of available material. Thus, all that can actually be stated is that the JANGLE data do not preclude the possibility that the breakup of concrete source material caused by a nuclear shot obeys the same

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*"Broken Coal II", J. G. Bennett, B. L. Brown, and H. G. Crane, J. Inst. Fuel, 14, III, '41. The "Ideal Breakage Law" specified is

$$M(x) = 1 - e^{-\frac{x}{\bar{x}}}$$

where M is the fraction of the total weight in pieces smaller than size x, and $\bar{x}$ is the "characteristic" size.

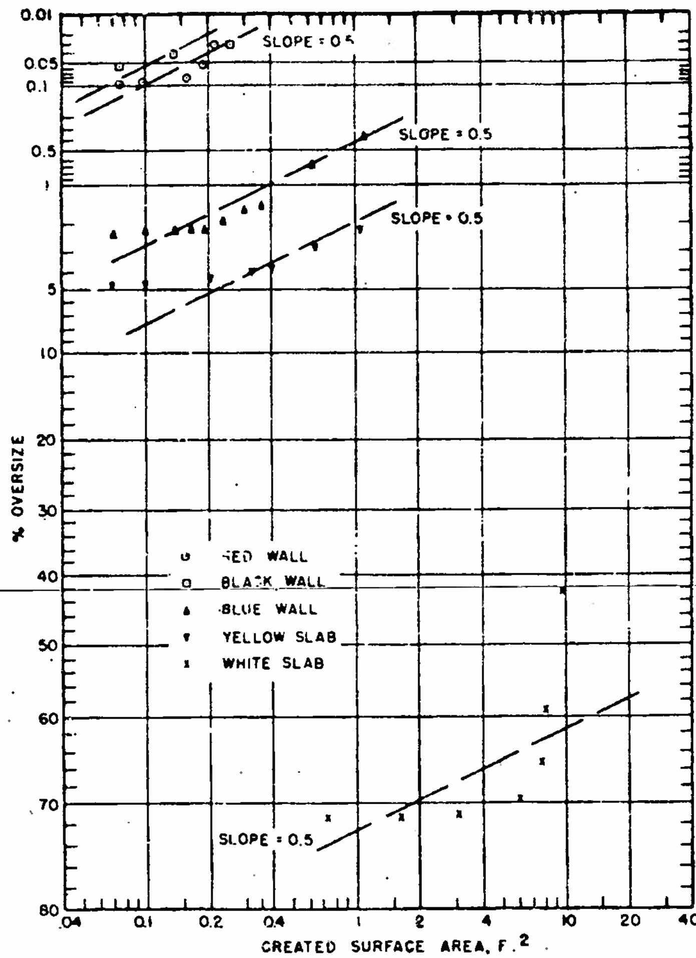

Figure 5.1 Size Distribution of Missiles. Theoretical Slope = 0.5

laws as does coal in a mine or ore in a crusher.

As a minor part of the interior ballistics or early behavior of missiles the high temperature close to the explosion is of interest. It appears probable that an important fraction of missile source material is vaporized and in addition small fragments are still further reduced in size by the high temperature; some fragments of size 1 inch to 6 inches show a great loss in strength as well as change in color (note Figure 4.6). These effects are probably due to the high temperature. The over-all result of this high temperature is to reduce the damage caused by missiles. This is true because that part of the missile source which would otherwise be thrown out with any but small elevation angles is instead vaporized and hence airborne.

The final aspect of interior ballistics to be considered is the initial velocity which is imparted to missiles. As a result of the Dugway experiments it was concluded that missile velocities are related to the elevation angles of exit approximately by the relation $v = V \sin^2\theta$, where v is the initial velocity of the missile, V is the velocity of the earth directly over the charge, and θ is the elevation angle of the slant radius from the charge center to the missile. However, in extrapolating to the JANGLE shot, it must be noted that the missiles of importance at JANGLE were those which had very small values of θ, while the Dugway missiles to which most attention was directed in developing the equation were relatively high angle missiles. In fact, the low angle missiles at Dugway deviated rather significantly from this relation.

A further assumption made at Dugway needs reconsideration in extrapolation of the JANGLE results. This is the assumption that the initial velocity of missiles is along the slant radius from the charge center to the initial location of the missile source. Both photographic evidence and analysis indicate that at least in the later stages of the throwout process there is a scouring action by which material originally lower than the charge center is thrown out around the lip of the crater. This material undoubtedly has a greater elevation angle than that indicated by the slant radius. Presumably missiles which are originally on the surface are thrown out at an earlier stage in the process and hence this consideration may not be pertinent.

Finally, it is entirely possible that the gross differences in soil characteristics at Dugway and at JANGLE may have important effects on many aspects of missile formation and ejection.

5.2 EXTERIOR BALLISTICS

The behavior of missiles after they have left the immediate vicinity of an underground explosion has been established by the experiments at Dugway and at JANGLE with a reliability which is probably adequate in view of the gross uncertainties in the interior ballistics. Figures 5.2 and 5.3 are elevation drawings of the highway and wall targets. The missiles of a size to be of military importance at JANGLE all had elevation angles less than 20 degrees and initial velocities less than 600 feet per second. For this group of missiles the air drag is not of major importance and calculations based on vacuum ballistics would be almost adequate. The most important consideration is that trajectories are very flat and the maximum height of the missiles is less than 200 feet or 300 feet.

Considerable support for the practical accuracy of both the break-up and range assumptions was derived from a detailed analysis carried out on missiles from the blue wall. In outline, the analysis consisted of the following steps:

a. Data on the 102 blue missiles were plotted, number vs. size.

b. The curve so obtained was assumed to apply to the whole wall.

c. The mass of the wall (in the 5 degree sector from which missiles were collected) was calculated for each 1 degree increment of θ from the bottom to the top, taking into account the dimensions of the wall. (See Figure 5.3).

d. This mass was divided into four weight categories (of equal numbers of missiles) according to the distribution described in "b" and the probable range determined for each weight group in each 1 degree θ -interval.

e. The predicted relative concentration of each size at each range was then plotted.

f. This plot was compared with that for the missiles actually picked up. Figure 5.4 shows this comparison between calculated and actual distribution for the largest weight category.

The coincidence seems remarkably good: a double-peaked distribution for each size was predicted, with one peak occurring inside the 1500 foot minimum for the collection strip and the other peak occurring on the beginning of the strip. The first peak could not be checked, of course, but the second, in the case of the two weight categories analyzed, actually occurred within 200 feet of the location predicted by the analysis.

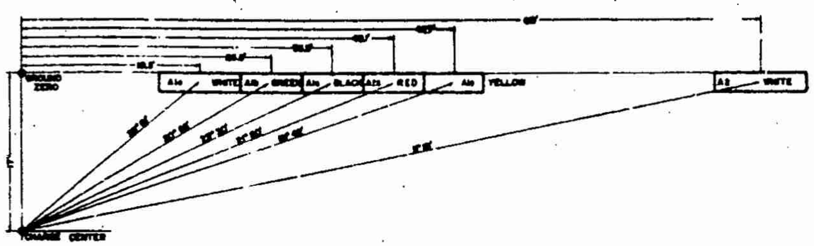

Figure 5.2 Elevation of Highway Slab Targets A-1 and A-2

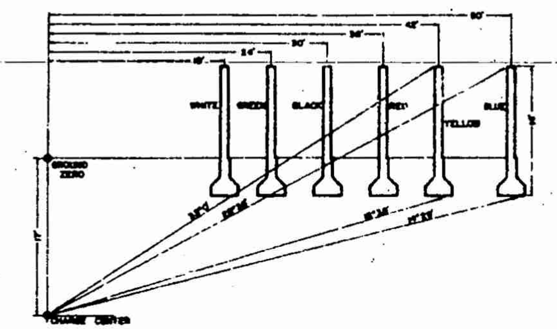

Figure 5.3 Elevation of Wall Targets

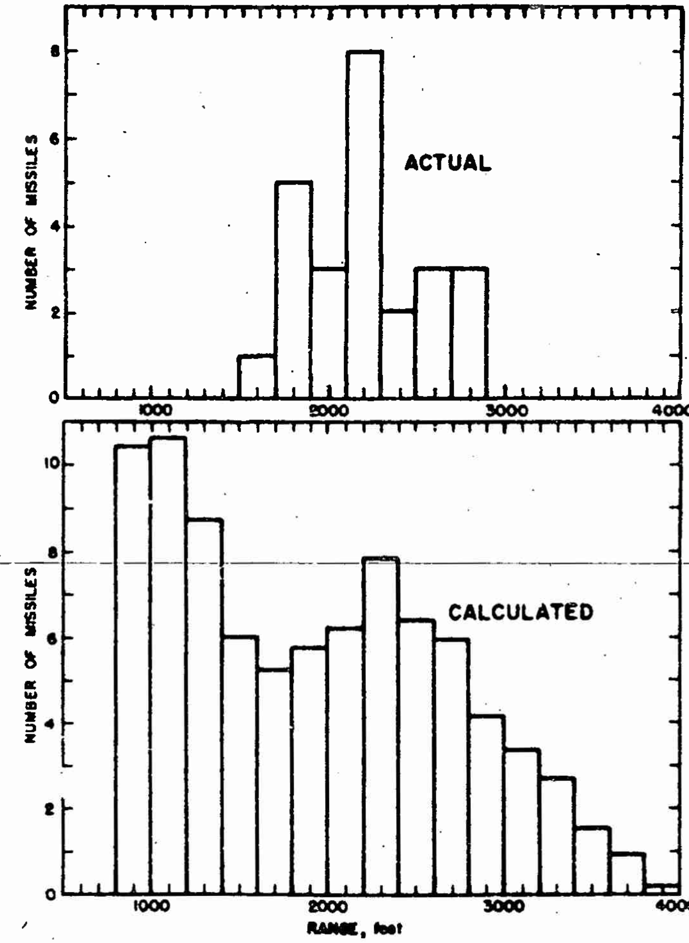

Figure 5.4 Calculated and Actual Range Distributions of Large Blue Wall Missiles

Since the total weight of the blue missiles picked up was only about 3 percent of the weight of the wall in that 5 degree sector, it would not have been surprising if this small sample had behaved very differently from a prediction made for the whole wall sector.

5.3 EXTRAPOLATIONS

Since the causes of breakup are not well established, there is considerable uncertainty when one attempts to extrapolate the JANGLE results to a larger explosion. Specifically, one might assume that it is the maximum energy-density at a given point which is the determining factor in breakup. On the other hand, it might be argued that it is the peak acceleration produced in the soil which is crucial.

If one assumes that breakup depends on peak energy-density (and it is believed that this is the most tenable assumption), then a missile source at a given scaled radius (λ_o) will be broken up into the same distribution of sizes on two scaled explosions (that is, where λ_o is the same). These missiles will have exterior ballistic flight identical to those at JANGLE. Since 1 foot to 4 foot missiles were thrown to distances of 1000 feet to 1200 feet from the rim of the crater at JANGLE, missiles of this size should then be found at the same actual distance from the new crater rim (not scaled) on any size explosion (at the same λ_c).

If breakup depends on peak acceleration, then when the JANGLE test is scaled up to an energy release S^3 times as large, missiles having a size of military importance will be produced at a smaller scaled radius than if the other assumption of breakup is made.* These missiles will have higher elevation angles and greater ranges (if they survive thermal destruction), but the density of missiles arriving will be very much less, both because the source of missiles is smaller (at a smaller radius) and because the interval of ballistic flight and therefore dispersion is greater due to the higher elevation angle.

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*The scaled radius at which the peak acceleration is identical will depend both on scaling and on the fall-off of acceleration with radius on any explosion. By scaling laws $A_2 = A_1(\frac{1}{S})$ where $\lambda_2 = \lambda_1$.

If on any one explosion $A = k\lambda^{-n}$, then the acceleration will be the same on two scaled shots when $\lambda_2 = \lambda_1(S)^{-\frac{1}{n}}$. ($A = k\lambda^{-n}$ is based on experimental evidence.)

If $n = 2$, $S = 3$ then $\lambda_2 = \lambda_1(3)^{-\frac{1}{2}} \approx 0.6\lambda_1$

5.4 CALCULATION OF POTENTIAL DAMAGE

The results of the JANGLE test have been studied and analyzed so as to obtain the firmest possible answers to two questions: first, what damage can be expected by missiles from a large underground explosion (and how this compares to the damage produced by air blast or ground shock); second, should a missile experiment be included if another underground test is performed.

While it is not the purpose here to discuss in definitive terms the military aspects of the JANGLE experiment, it appears useful to outline the military context into which the conclusions of this experiment must fit.

As was mentioned in the Introduction, the over-all function of the missile study was to assist in evaluation of the usefulness of an underground weapon versus an air-burst or surface-burst weapon. Three types of targets merit consideration in this connection (under the assumption that other types of targets are surely better attacked by air or surface bursts). These three are:

a. Deep fortifications
b. Urban areas
c. Air fields

In attacking deep fortifications it seems clear that underground weapons are important. However, against such targets essentially no damage is produced by missiles and hence the evaluation of the missile situation is unimportant.

Against urban areas, particularly business or industrial areas, air-burst weapons are believed to give greater radius of important damage than underground bursts. If an underground weapon is detonated in such an area, there are sufficient buildings to constitute an important source of missiles, but by the same token there will be surrounding buildings which will absorb all of the low trajectory missiles early in their flight. High trajectory missiles, if they survive thermal destruction, would land at great distances and therefore at very low densities which would not be a source of important damage to buildings. Both because the air burst seems more effective and because the highly concentrated missiles formed from an underground burst will be stopped quickly, precision in the evaluation of the effectiveness of missiles against urban built-up areas is not warranted.

In attacking air fields the primary military objective is ordinarily to deny use of the air field for the maximum possible time. In general this requires gross damage to the air strip itself. Secondary

objectives may be destruction or damage to airplanes and surface buildings. To produce gross damage to an airstrip, an underground burst is undoubtedly the most effective weapon. In regard to the airstrip itself, the residual damage caused by missiles is altogether trivial. In regard to airplanes and buildings, the damage due to missiles may be as large as or larger than that produced by ground shock or air blast. It appears that this is the only situation in which precise knowledge of missile behavior might be of significant value. Since missile damage to planes and buildings is still of secondary importance, it is doubted that the precise evaluation of such damage is worth more than a minor expenditure of effort.

Under some circumstances damage to planes or buildings may be the primary objective. In this case an air burst would be more effective and hence again precise evaluation of missile damage is not important.

5.4.1. Damage to Buildings

Assessment of the damage to buildings produced by missiles involves several intangibles. Steel frame or concrete buildings may be pierced by large missiles but would probably not be damaged beyond easy repair unless more than one major column was buckled by impact with a large missile or unless the total momentum of material striking the building was sufficient to produce its collapse. Actually, in producing collapse, the total moment of momentum is probably more significant than the momentum itself, since in such cases failure may be expected to occur first at the bottom of the columns, and it is clear that the momentum of a group of missiles striking the side of the building near its top will produce twice the overturning moment as the same momentum of missiles striking the building halfway up. On the other hand, the effect of missiles, particularly those with flat trajectories, will produce much the same forces as are produced by wind, and taller buildings are designed with greater resisting moments in the column joints.

The best means immediately available of estimating the total momentum of missiles required to collapse a building is contained in the Surface Structure Tests at Dugway.* In these tests several structures collapsed as a result of the impact of throwout material. While the structures were far from typical buildings, they were intended to

*Final Report, "Surface Structure Program, Underground Explosion Tests at Dugway", Stanford Research Institute. Prepared for Sacramento District Office, Corps of Engineers, U. S. Army, March 1952. CONFIDENTIAL SECURITY INFORMATION.

have roughly the same strengths, and while the missiles under discussion are considerably different from the throwout material at Dugway, it is believed appropriate to consider the total momentum the most important parameter. Looking at the Dugway experiments, it is estimated that Structures A, D, and E were struck with throwout having about three times the momentum required to produce collapse. By assuming (1) a frontal wall for these structures and (2) that one-third of the actual missile (or throwout) momentum was distributed over it, it is estimated that the momentum density required to produce collapse is roughly 150 slug feet per second per square foot.

Consideration of all the available information suggests that a peak of missile momentum density will always occur at the crater lip because, if source material is available there, it will have the lowest possible trajectory and therefore the greatest concentration. If the slant radius to the crater rim has an elevation angle greater than, say, 15 degrees, the trajectory will be high enough so that simple radial dispersal as well as elevational dispersal of the material there will quickly reduce its density below a critical level. However, if the crater size is such that the slant radius from charge to rim forms an angle of 15 degrees or less with the horizontal, intensive missile damage can be predicted (assuming the presence of source material) in an area just outside the rim. This damage area increases with increasing charge size but far less rapidly than the scale factor.

The results of the JANGLE experiment indicate that a peak of missile momentum density would probably have occurred at around 140 feet from ground zero (i.e. at the crater lip) if the highway slab had been continuous. This would have been the order of 5 times as much as necessary to demolish an ordinary building.

Beyond this peak the density could be expected to taper off so that at about 1000 feet from ground zero the density is only one-third the amount necessary for severe building damage, with the critical distance being the order of 600 - 800 feet from ground zero. Peak air-blast pressure at 750 feet from ground zero was about 10 psi, which is also considered critical for ordinary buildings.

Extrapolation to an explosion having an energy release S^3 times as large, along with the assumption of breakup determined by energy-density, results in the calculation of a maximum density of missile momentum at the rim of the larger crater which is roughly S times that for JANGLE, if S is the order of 3 (that is, if $S^3 \approx 25$). Similarly it is expected that the critical distance for severe damage would now be the order of 1100 feet from ground zero. This should be compared with 10 psi air blast predicted at 2250 feet from ground zero, or with 20 psi at 1100 feet. Thus buildings should be expected to sustain

damage by the mechanism of air blast out to roughly twice the distance where they will sustain damage by the mechanism of missiles.

Extrapolation to a shot having S^3 times the energy release under the assumption that breakup depends on peak acceleration results in very similar conclusions. Here too, although breakup would be very different, the only location where missile trajectories would be flat enough to yield high concentrations of missile momentum would be again at the crater lip. Large pieces might be predicted to travel at velocities in the neighborhood of 100 feet per second essentially along the ground and to do considerable damage to anything in their paths nearer than 1000 feet or so. There is no evidence for this theory of breakup, however.

Comparison of the critical damage radius by missiles with the critical damage radius produced by ground motion was considered pertinent before the experiment, but has been found to be unimportant because the critical radius due to air blast from such shallow explosions is definitely larger than that due to ground motion.

5.4.2. Damage to Airplanes

Since damage to airplanes may be a secondary objective of an attack on an air field with an underground weapon, the effect of missiles in this regard needs to be considered. Several differences from the analysis of damage to buildings are at once apparent. Among these are:

a. Airplanes, particularly high speed planes, may sustain important damage as a result of impact by even a few relatively small missiles. Thus the momentum of missiles or momentum density is not an appropriate criterion of damage.

b. Airplanes around airfields are commonly protected by revetments, which are particularly effective against missiles having flat trajectories.

Thus under the assumption of breakup determined by energy-density, the missiles at JANGLE to which attention was devoted for building damage would be ineffective because they would be stopped by the barricades. However, since it is possible that even missiles smaller than 2 inches might produce some damage to airplanes, analysis was carried on to estimate the incidence of individual missiles at much greater distances. Predictions are difficult because the smallest missiles were not extensively studied at JANGLE.

However, using all the available data, the ballistic curves developed from the Dugway experiment and from the Rand studies, together

with the present knowledge with regard to scaling, it has been estimated that an underground nuclear explosion with an energy release about 25 times as large as that at JANGLE (S = 3) fired under a continuous concrete slab would produce very roughly the following missile concentrations at the specified ranges:

Underground Nuclear Explosion: S = 3 (JANGLE, S = 1), λ_c = 0.15

Approximate Number of Missiles Predicted to Fall in a 100 Foot^2 Area

Range	Missile Size and Angle of Entry: Small		Medium		Large	
1700 feet	300	40°-50°	2	20°	1	13°
2200 "	75	45°	3	25°	1	14°
2700 "			1	40°	<1	14°
3200 "					<<1	25°

Typical wing area of planes is about 200 feet^2 for a single-engine plane to over 2000 feet^2 for heavy four-engine bombers.

Small: .8 inches to 2.8 inches in diameter. Medium: 2.8 inches to 6.4 inches in diameter. Large: 6.4 inches to 30. inches in diameter.

These values must be considered in the light of extrapolated predictions for air-blast values on such a shot: 3 psi peak at 6000 feet and 8 psi peak at 3000 feet. On this basis airplanes should be expected to sustain damage by the mechanism of air blast out to roughly twice the distance where they will sustain damage by the mechanism of missiles.

The comparison of the critical damage radius due to missiles with that due to air blast may be modified by the effect of soil characteristics. Comparison of the air blast from HE-3 at the Nevada Site with Round 315 at Dugway (both 2560 pounds TNT at λ_c = 0.5) shows that the air blast at Dugway was roughly one-half that at Nevada. While comparative figures at other depths are not available, it seems obvious that the air blast due to charges on the surface (λ_c = 0) will be unaffected by the soil characteristics. From this presumption and the comparison just mentioned at λ_c = 0.5, it is felt to be safe to predict that the air-blast pressure produced by an underground explosion as shallow as λ_c = 0.15 will not be significantly affected by soil characteristics. Experimental information on this point will be obtained on programs currently in progress.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

It is concluded that an underground explosion having 25 times the energy release of the JANGLE underground shot at the same scaled depth of burial (λ_o = .15), fired beneath a continuous concrete runway 18 inches thick, would produce missiles which would seriously damage or destroy buildings out to a radius of about 1100 feet or airplanes on the ground out to about 3000 feet.

The same underground explosion would, as a result of air blast, produce major damage to buildings out to a radius of about 2200 feet and damage to airplanes out to a radius of about 6000 feet.

For still larger underground explosions the damage radius of missiles increases at a slower rate than the damage radius of air blast, which is proportional to $W^{1/3}$.

6.2 RECOMMENDATIONS

Further study of the missile problem is not justified unless corrections are found to be necessary in either (a) the discussion of military aspects contained in this report, or (b) the radius assumed here of significant damage to buildings or airplanes by the mechanism of air blast from underground explosions.

24

END